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RAM PIPE REQUAL: A RISK ASSESSMENT & MANAGEMENT BASED PROCESS FOR THE REQUALIFICATION OF MARINE PIPELINES

R. G. BEA*

ABSTRACT

This paper proposes a general engineering approach for risk assessment and management (RAM) of marine pipeline systems. The system is identified as *RAM PIPE REQUAL*. The approach is based on use of qualitative, quantitative, and mixed qualitative – quantitative analytical methods. Both qualitative and quantitative analytical methods have found widespread use in risk assessment and management of pipelines (Muhlbauer 1992; Kirkwood, Karam, 1994; Kulkarni, Conroy, 1994; Nessim, Stephens, 1995; Collberg, Cramer, Bjornoy 1996; Office of Pipeline Safety, 1997; Zimmerman, et al 1998; Bai, Song, 1998). This paper will outline the approach, its attributes and strategies, and further develop the qualitative – quantitative approach for design and reassessment of pipelines subjected to corrosion. The paper is introduced with a general overview of the premises and strategies for RAM of engineered systems.

INTRODUCTION

During the past two years, the U. S. Minerals Management Service in cooperation with Petroleos Mexicanos (PEMEX) and Instituto Mexicano del Petroleo (IMP) have sponsored and directed development of a general risk assessment and management (RAM) based process for the reassessment and requalification of marine pipelines. This paper summarizes the work done to develop this process.

Practicality is one of the most important attributes of an engineering approach. Industry experience indicates that a practical RAM pipeline reassessment and requalification approach should embody the following attributes:

- **Simplicity** – ease of use and implementation,
- **Versatility** – the ability to handle a wide variety of real problems,
- **Compatibility** – readily integrated into common engineering and operations procedures,
- **Workability** – the information and data required for input is available or economically attainable, and the output is understandable and can be easily communicated,
- **Feasibility** – available engineering, inspection, instrumentation, and maintenance tools and techniques are sufficient for application of the approach, and
- **Consistency** – the approach can produce similar results for similar problems when used by different engineers.

A general RAM based approach for the reassessment and requalification of marine pipelines is developed in this paper. The approach is identified as RAM PIPE. The RAM PIPE approach is founded on the following key strategies:

- Keep pipeline systems in service by using preventative and remedial IMR (Inspection, Maintenance, Repair) techniques. RAM PIPE attempts to establish and maintain the integrity of a pipeline system at the least possible cost.
- RAM PIPE procedures are intended to lower risks to the minimum that is practically attainable. Comprehensive solutions may not be possible. Funding and technology limitations may prevent implementation of ideally comprehensive solutions. Practicality implicates an incremental investment in identifying and remedying pipeline system defects in the order of the hazards they represent. This is a prioritized approach.
- RAM PIPE should be one of progressive and continued reduction of risks to tolerable levels. The investment of resources must be justified by the scope of the benefits achieved. This is a repetitive, continuing process of improving understanding and practices. This is a process based on economics and benefits.

RISK ASSESSMENT & MANAGEMENT

Risk can be characterized as the likelihood that adequate or acceptable quality is not achieved and the consequences associated with the lack of achieved quality. Quality is characterized as the desirable combination of serviceability, safety, durability, and compatibility. Risk results from uncertainties. Uncertainties result from: inherent variability (natural, aleatory), professional or technical sources (analytical, modeling, parameter, information, epistemic), and human and organizational factors. Risk assessment attempts to understand and identify the risks and how they might be mitigated. Risk management attempts to evaluate alternative measures for risk mitigation, identify those that should be implemented, and then plan, organize, lead, and control the implementation.

Some uncertainties are random (aleatory) and some are systematic (epistemic). Some uncertainties can be managed (information sensitive, epistemic, predictable), and some uncertainties can not be managed (information insensitive, aleatory, unpredictable). Some uncertainties are essentially static (unchanging in time) and others are very dynamic. Some uncertainties can be identified and quantified and some uncertainties can not be identified and quantified (unknowable).

Consequences result from unrealized expectations and unanticipated lack of sufficient quality. Consequences can be expressed in terms of their frequency, their severity, their impacts (on site and off site), and their predictability. Consequences can be expressed in a variety of ways

* Professor, Department of Civil & Environmental Engineering, Marine Technology & Management Group, 212 McLaughlin Hall, University of California at Berkeley, Berkeley, CA 94720, (925)642-0967, e-mail: bea@ce.berkeley.edu

and with a variety of metrics. Monetary costs are one metric to measure and express consequences. Time (schedule, availability), injuries to humans, and injuries to the environment are other ways to express and measure consequences.

Some consequences can be proactively managed or controlled (hazard mitigation measures). Some consequences can not be proactively managed or controlled. Some consequences can be evaluated objectively and quantitatively and some consequences can not be evaluated objectively and quantitatively. Some consequences are essentially static. Other consequences are very dynamic in that they change markedly with time. Generally, there are significant uncertainties associated with the results of evaluations of consequences. This is particularly so as one projects the consequences of insufficient or unacceptable quality far into the future. Evaluations of consequences are difficult to make and express.

Evaluations of consequences are very susceptible to the values, views, and biases of the assessors. Studies of evaluations of risks indicate that organizational biases frequently dominate assessments of risk made by personnel in the organization. The studies suggest that the profit incentives underlying organizational biases for risk taking appears to overcome personal biases favoring risk avoidance. The potential for such biases are particularly important when the risk assessments are made by an organization's engineers. The engineer's training and discipline as a servant to the organization can impart some very strong organizational biases in the assessment of risk.

An identified risk is an engineering and management problem. A faulty or bad definition of a risk can result in additional risk and result in bad management of safety. A risk management framework should be based on intelligent and perceptive risk identification, classification, analysis, evaluation, and response. Risk management attacks both the likelihoods of compromises in quality and the consequences associated with these compromises.

Risks have sources, are translated to reality with events, and are felt with effects. There are initiating events (direct causes), contributing events (background causes), and compounding events (propagating or escalating or arresting causes). Risk management attempts to identify and remedy causes, detect potential and evolving events and bring them under control, and minimize undesirable effects.

Risks are independent and dependent. Risks can have partial dependence. If the occurrence of one risk does not influence the occurrence of another risk, then it is independent. If the magnitude of one risk is related to the magnitude of another risk then these two risks are correlated. Independence and correlation are critical issues in risk analysis, evaluation, and management.

Risks are controllable and uncontrollable. Controllable risks are those that are within the direct control of those that own, operate, maintain design, classify, regulate, and build engineered systems. Uncontrollable risks are those that are not within the direct control of these groups. Proactive risk management is concerned primarily with predictable and controllable risks. Reactive risk management is concerned primarily with preventing future accidents based on experience from past accidents. Reactive or 'real-time' risk management is concerned primarily with unpredictable – unknowable risks. Inherent risk and uncontrollable risk must be recognized, evaluated, and managed in the process of making decisions regarding the activities and ventures associated with engineered systems.

A risk management system should be practical, realistic, and must be cost effective. Risk management need not be complicated nor require the collection of vast amounts of data. Excellent risk management results from a combination of uncommon common sense, qualified experience, judgment, knowledge, wisdom, intuition, trust, and integrity. Mostly it is a willingness to operate in a caring and disciplined manner in approaching the critical features of any activity in which risk can be generated. Risk management is largely a problem of doing what we know we should do and not doing what we know we should not *do.*

The purpose of a RAM system should be to enable and empower those that have direct responsibilities for the designing, building, maintaining, and operating engineered systems. The engineer can play a vital role in this empowerment. If technology is not used wisely, scarce resources and attention can be diverted from the true factors that determine the safety of an engineered system, and less safe systems developed. The purpose of a RAM system should be to assist the front line operators to take the right (sensible) risks and to achieve acceptable quality and reliability. To try to completely eliminate risk is futile. To help manage risks and make appropriate use of technology should be one of the key objectives of RAM.

A detailed study of information from more than 600 well documented failures of engineered systems indicates that the primary threats to the quality and reliability of these systems are posed by people; the individuals that are the system operators throughout its life-cycle (design, construction, operation, maintenance, decommissioning) and the organizations that determine in large measure the incentives, resources, and performance characteristics of the system operators (Bea, 1999). Something of the order of 80 % of failures to achieve adequate and desirable quality and reliability are due to HOF (Human and Organizational Factors). About 80 % of these compromises occur during operations and maintenance; however, many of these compromises have sources in design and construction misadministrations. Inappropriate and in some cases seriously flawed designs are passed to construction; construction attempts to work around them and perhaps the construction process adds a few defects and flaws; a seriously flawed system is passed to operations where perhaps additional maintenance flaws and defects are added. The final product is an accident waiting to happen and it often happens during operations.

This same study indicates that while the majority of initiating events can be traced to 'operator' malfunctions that are most often errors of commission (act or acts carried out incorrectly or with incorrect intentions, the majority of contributing events can be traced to 'organizational' malfunctions. These contributing events act to dramatically escalate the likelihoods of operator malfunctions. The majority of compounding events that allow the initiating events to escalate into an accident also can be traced to organizational malfunctions. It is clear that organizations have major influences on the quality and reliability of marine systems. Any competent RAM system must effectively address the HOF aspects that exert major influences on the quality and reliability of engineered systems.

The research and experience on which this paper is based indicates that there are three fundamental approaches to achieving adequate and acceptable quality and reliability in engineered systems (Bea, 1999):

- **Proactive**,
- **Reactive**, and
- **Interactive or real-time.**

Proactive Approaches

The proactive approach attempts to analyze the system before it fails in an attempt to identify how it could fail in the future. Measures can then be put in place to prevent the failure or failures that have been anticipated. Proactive approaches include well developed qualitative methods such as HazOp (Hazard Operability) and FMEA (Failure Mode and Effects Analyses) and quantitative methods such as PRA (Probabilistic Risk Analyses) and QRA (Quantified Risk Analyses). Each of these methods have benefits and limitations.

The author was an active protagonist and practitioner of the proactive PRA/QRA approach for more than three decades. He believed that this approach provided an ability to forecast how systems could go bad. Very sophisticated PRA models could be developed to help foster this belief. The results from these analyses seemed to have value and to enhance his abilities to address some types of uncertainty. This approach was workable as long as he dealt with systems in which the interactions of people with the systems were minimal or minimized. However, the problem changed radically when people began to exert major influences on the safety of the systems and in many cases on the physical aspects of the systems. In this case, his lack of knowledge of the physics and mechanics of the complex behaviors of people that in the future would design, construct, operate, and maintain the system defined an unpredictable system, or certainly one with very limited predictability. The author's analytical models addressed systems that were essentially static and mechanical. Yet the real systems were dynamic, constantly changing, and more organic than mechanical. The analytical models generally failed to capture the complex interactions between people and the systems that they designed, constructed, operated, and maintained.

The author found most data on the reliability of humans in performing tasks to be very limited. Existing databases failed to capture or adequately characterize influences that had major effects on human reliability. Yet, when the numbers were supplied to the very complex analytical models and the numbers were produced, the results were often mistaken for 'reality.' There was no way to verify the numbers. If the results indicated that the system was safe, then nothing was done. If the results indicated that the system was unsafe, then generally equipment and hardware fixes were studied in an attempt to define a fix or fixes that would make the system safe, or 'as safe as reasonably possible.' When the author went to the field to compare his analytical models with what was really there, he found little resemblance between his models and what was in the field.

The author does not advocate discarding the analytical - quantitative proactive approach. He advocates using different types of proactive approaches to gain insights into how systems might fail and what might be done to keep them from failing. The marked limitations of analytical models and quantitative methods must be recognized or major damage can be done to the cause of system safety. On the other hand, qualitative methods (e.g., HazOp, FMEA), in the hands of qualified and properly motivated assessors (both internal and external) can do much to help the causes of quality and reliability. Experience, judgment, and intuition of the assessors needs to be properly recognized, respected, and fully integrated into proactive qualitative and quantitative approaches.

It is the author's experience in working with and on engineered systems for more than four decades, that many if not most of the important proactive break-throughs in the quality and reliability of these systems were originated in a cooperative. trust-based venture of a knowledgeable 'facilitator' working with seasoned veterans that had daily responsibilities for the quality of these systems. This cooperative venture includes design, construction / decommissioning, operations, and maintenance / inspection personnel. Yet, it also is the author's experience, that many engineering and many well meaning safety personnel and human factor experts are not developing a cooperative environment. This is very disturbing. The conduct of each operation during the life-cycle of an engineered system should be regarded as the operations of 'families'. Knowledgeable, trained, experienced, and sensitive outsiders can help, encourage, and assist families to become safer or better. But, they can not make the families safer or better. Families can only be changed from within by the family members. Safety measures based on casual or superficial knowledge of a system or of an operation of that system should be regarded as tinkering. And, tinkering can have some very undesirable effects and results.

The crux of the problem with proactive PRA/QRA approaches is with the inability of such approaches to be able to fully capture the future human and organizational factors and their effects on the performance of a system. PRA/QRA rely on an underlying fundamental understanding of the physics and mechanics of the processes, elements, and systems that are to be evaluated. Such understanding then allows the analyst to make projections into the future about the potential performance characteristics of the systems. And, it is here that the primary difficulties arise. There is no fundamental understanding of the physics and mechanics of the future performance – behavior characteristics of the people who will come into contact with a system and even less understanding of the future organizational influences on this behavior. One can provide very general projections of the performance of systems including the human and organizational aspects based on extensive assumptions about how things will be done, but little more. The problem is that engineers start believing that their numbers represent reality.

To the author, the true value of the proactive PRA/QRA approach does not lie in its predictive abilities. The true value lies in the disciplined process PRA/QRA can provide to examine the strengths and weaknesses in systems; the objective is detection and not prediction. The magnitudes of the quantitative results, if these results have been generated using reasonable models and input information, can provide insights into where and how one might make the system better and safer. The primary problems that the author has with PRA/QRA is with how this method is used and what it is used to do. Frequently the results from PRA/QRA are used to justify meeting or not meeting regulatory / management targets and, in some cases not implementing clearly justified – needed improvements in the quality – reliability of an engineered system.

Reactive Approaches

The reactive approach is based on analysis of the failure or near failures (incidents, near-misses) of a system. An attempt is to made to understand the reasons for the failure or near-failures, and then to put measures in place to prevent future failures of the system. The field of 'worker safety' has largely developed from application of this approach.

This attention to accidents, near-misses, and incidents is clearly warranted. Studies have indicated that generally there are about 100+ incidents, 10 to 100 near-misses, to every accident. The incidents and near-misses can give early warnings of potential degradation in the safety of the system. The incidents and near-misses, if well understood and communicated provide important clues as to how the system operators are able to rescue their systems, returning them to a safe state, and to potential degradation in the inherent safety characteristics of the system.

Well developed guidelines have been developed for investigating incidents and performing safety audits associated with near-misses and accidents. These guidelines indicate that the attitudes and beliefs of the involved organizations are critical in developing successful systems, particularly doing away with 'blame and shame' cultures and practices. It is further observed that many if not most systems focus on 'technical causes' including equipment and hardware. Human – system failures are treated in a cursory manner and often from a safety engineering perspective that has a focus on outcomes of errors (e.g. inattention, lack of motivation) and statistical data (e.g. lost-time accidents).

A primary objective of incident reporting systems is to identify recurring trends from the large numbers of incidents with relatively minor outcomes. The primary objective of near-miss systems is to learn lessons (good and bad) from operational experiences. Near-misses have the potential for providing more information about the causes of serious accidents than accident information systems. Near-misses potentially include information on how the human operators have successfully returned their systems to safe-states. These lessons and insights should be reinforced to better equip operators to maintain the quality of their systems in the face of unpredictable and unimaginable unraveling of their systems.

Root cause analysis is generally interpreted to apply to systems that are concerned with detailed investigations of accidents with major consequences. The author has a fundamental objection to root cause analysis because of the implication that there is a single cause at the root of the accident. This is rarely the case. This is an attempt to simplify what is generally a very complex set of interactions and factors, and in this attempt, the lessons that could be learned from the accident are frequently lost. Important elements in a root cause analysis includes an investigation procedure based on a model of accident causation. A systematic framework is needed so that the right issues are addressed during the investigation. There are high priority requirements for comprehensiveness and consistency. The comprehensiveness needs to be based on a systems approach that includes error tendencies, error inducing environments, multiple causations, latent factors and causes, and organizational influences. The focus should be on a model of the system factors so that error reduction measures and strategies can be identified. The requirement for consistency is particularly important if the results from multiple accident analyses are to be useful for evaluating trends in underlying causes over time. There is no shortage of methods to provide a basis for detailed analysis and reporting of incidents, near-misses, and accidents.[4-9] The primary challenge is to determine how such methods can be introduced into the life-cycle of engineered systems and how their long-term support can be developed.

Inspections during construction, operation, and maintenance are a key element in reactive RAM approaches. Thus, development of IMR (Inspection, Maintenance, Repair) programs is a key element in development of reactive management of the quality and reliability of engineered. Deductive methods involving mechanics based probability techniques have been highly developed. These techniques focus on 'predictable' damage that is focused primarily on durability. Inductive methods involving discovery of defects and damage are focused primarily on unpredictable elements that are due primarily to unanticipated HOE such as weld flaws, fit-up or alignment defects, dropped objects, ineffective corrosion protection, and collisions. Reliability Centered Maintenance (RCM) approaches have been developed to help address both predictable and unpredictable damage and defects (Jones, 1995).

The reactive approach has some important limitations. It is not often that one can truly understand the causes of accidents. If one does not understand the true causes, how can one expect to put the right measures in place to prevent future accidents? Further, if the causes of accidents represent an almost never to be repeated collusion of complex actions and events, then how can one expect to use this approach to prevent future accidents? Further, the usual reaction to accidents has been to attempt to put in place hardware and equipment that will help prevent the next accident. Attempts to use equipment and hardware to fix what are basic HOF problems generally have not proven to be effective. It has been observed that progressive application of the reactive approach can lead to decreasing the accepted 'safe' operating space for operating personnel through increased formal procedures to the point where the operators have to violate the formal procedures to operate the system.

Interactive Approaches

Experience with the safety and quality of engineered systems indicates that there is a third important approach to achieving safety that needs to be recognized and further developed. This approach is interactive (real-time) management of 'crises' in which danger builds up in a system and it is necessary to actively intervene with the system to return it to a safe state. This approach is based on the contention that many aspects that influence or determine the failure of systems in the future are fundamentally unpredictable and unknowable. In the context of the life-cycle of engineered systems, crises are an everyday thing. Crises are the incredible, unbelievable, complex sequences of events and developments that unravel a system until it fails. This approach is based on providing systems (including the human operators) that have enhanced abilities to rescue themselves. This approach is based on the observation that people more frequently return systems to safe states than they do to unsafe states that result in accidents.

Engineers can have important influences on the abilities of people to rescue systems and on the abilities of the systems to be rescued by providing adequate measures to support and protect the operating personnel and the system components that are essential to their operations. Quality assurance and quality control (QA/QC) is an example of the real-time approach. QA is done before the activity, but QC is conducted during the activity. The objective of the QC is to be sure that what was intended is actually being carried out.

Two fundamental approaches to improving crisis performance are: 1) providing people support, and 2) providing system support. People support strategies include such things as selecting personnel well suited to address crises, and then training them so they possess the required skills and knowledge. Re-training is important to maintain skills and achieve vigilance. The cognitive skills developed for crisis management degrade rapidly if they are not maintained and used.

Crisis management teams should be developed that have the requisite variety to manage the crisis and have developed teamwork processes so the necessary awareness, skills and knowledge are mobilized when they are needed. Auditing, training, and re-training are needed to help maintain and hone skills, improve knowledge, and maintain readiness. Crisis management teams need to be trained in problem 'divide and conquer' strategies that preserve situational awareness through organization of strategic and tactical commands and utilization of 'expert task performance' (specialists) teams. Crisis management teams need to be provided with practical and adaptable strategies and plans that can serve as useful 'templates' in helping manage each unique crisis. These templates help reduce the amount and intensity of cognitive processing that is required to manage the crisis.

Improved system support includes factors such as improved maintenance of the necessary critical equipment and procedures so they are workable and available as the crisis unfolds. Data systems and communications systems are needed to provide and maintain accurate, relevant, and timely information in chunks that can be recognized, evaluated, and managed. Adequate safe haven and life saving measures need to be provided to allow crisis management teams to face and manage the crisis, and if necessary, escape. Hardware and structure systems need to be provided to slow the escalation of the crisis, and re-stabilize the system. Safety system automation needs to be provided for the tasks people are not well suited to perform in emergency situations.

One would think that improved system support would be highly developed by engineers. This does not seem to be the case. A few practitioners recognize its importance, but generally it has not been incorporated into general engineering practice or guidelines. Systems that are intentionally designed to be stabilizing (when pushed to their limits, they tend to become more stable) and robust (damage and defect tolerant) are not usual. Some provisions have been made to develop systems that slow the progression of some crises. Fire deluge systems, heat insulation on critical structural elements and fire walls, and blast pressure relief panels are examples of some of the provisions. The work on which this paper is based indicates that system robustness is achieved through a combination of configuration (alternative paths to carry the demands), ductility (ability to redistribute demands without compromising safety), and excess capacity (to carry the redistributed demands). These guidelines also apply to the organizational or people components of systems.

Effective early warning systems and crisis information and communication systems have not received the attention they deserve in providing system support for crisis management. Systems need to be designed to clearly and calmly indicate when they are nearing the edges of safe performance. Once these edges are passed, multiple barriers need to be in place to slow further degradation and there should be warnings of the breaching of these barriers. More work in this area is definitely needed.

Combined Approaches

The results of the experience and work on which this paper is based clearly indicate that a combination of proactive, reactive, and interactive approaches should be used to improve the quality and reliability of engineered systems. Each of these approaches has its strengths and weaknesses and their strengths need to exploited. The results of this work also clearly that in most cases, these approaches are not being used as well as they could be used.

In many instances, the reactive approach has resulted in development extensive rules and regulations that have become so cumbersome that they either are not used or are not used properly. Systems are more normally operated by 'informal' local operating procedures than by 'following the book.' Accident investigations frequently have turned into 'witch hunts' many times with the sole purpose of 'killing the victims.' Due to critical flaws in the accident investigation and recording processes, accident databases frequently fail to properly or reasonably capture the essence of how accidents develop or are caused.[4,9] Near-miss incidents have not received nearly the attention that they should.

In many instances, the proactive approach has developed into a quantitative ‘paper chase’ that has not yielded the benefits that it could yield. Numbers have been taken to represent the realities of future quality and reliability. Insights about how one might defend the system against unpredictable and unanticipated developments are lost in the complexities of the analyses. Experts are brought in to inspect and analyze the system and many times these experts do not possess the requisite experience or insights about how the system can unravel and fail. Fixes are general hardware oriented. Rarely do the HOF aspects receive any direct attention.

In general, the interactive approach has not received the attention that it deserves. In some non-engineering communities it has received extensive attention. These communities are those that daily must confront crises or the potential for crises. These crises all involve unpredictable and unknowable situations. Many of the communities have learned how to in most cases turn crises into successes. This work has not disclosed one instance in which the interactive approach has been used to address HOF in design engineering activities. Rarely has it been used in operations. Rather, safety meetings, drills and exercises are mistakenly taken to represent this approach.

RAM – PAST, PRESENT, FUTURE

In the past, RAM for marine systems has been founded primarily on experience. If a system or a component of a system worked, it was replicated. If a system or the component did not work, it was either discarded or revised, and tried again and revised until it worked. This trial-and-error approach is characteristic of the history and evolution many ‘engineered’ systems. The field of worker safety has largely evolved from this background, employing reactive safety management to try to prevent future accidents. Even in the case of marine systems that worked, the quest for more efficient, lower cost systems motivated the engineers to make modifications that in some cases eventually resulted in failures. Thus, marine engineering has more or less continuously migrated from failure to success.

Marine systems have had an interesting record of failures and successes. Some systems have proven to be remarkably reliable, while others have proven to be not so reliable. In the early days (after World War II), there were very high rates of failures. Then, the technology matured, and the rates of failures decreased markedly. In some areas, the failure rates again have risen largely in response to problems associated with older systems (marine geriatrics). Today, very high levels of technology are generally employed, and the systems generally have had a good record of success. The primary hazards to marine systems have proven not to be the ocean environment. Rather, the primary hazards to marine systems have proven to be founded in human and organizational factors.

In the recent past, RAM for marine systems has been addressed by design and requalification codes and guidelines. Fundamentally, this has been an attempt to reduce to written words and practice the hard-won experience associated with the trial and error, evolutionary approach to engineering marine systems. Codes and guidelines have taken two basic forms: prescriptive and goal setting. The prescriptive codes and guidelines detail how something should be done. The goal setting codes and guidelines detail what should be accomplished, and leave it to the engineer and system owner / operator to demonstrate that they are able to reach the goals. For most engineers, the goal setting approach does not contain sufficient information to allow a system to be either designed or requalified, and there is a drive to prescribe how the structure should be configured and operated so that it has acceptable and desirable performance characteristics.

The design guidelines for offshore platforms and pipelines in the U.S. Gulf of Mexico have largely embodied the prescriptive approach. Although, even the largely prescriptive guidelines contain goal associated statements and guidelines. The regulatory guidelines for offshore platforms and pipelines in the U.S. Gulf of Mexico are evolving from largely prescriptive requirements to goal requirements. But, even in this evolution, there is a mixture of prescriptive and goal oriented requirements.

The evolution in the North Sea has followed and is following a similar path. However, the regulatory component of the codes and guidelines has progressed farther along the goal setting path of development. In most of the North Sea communities, the regulatory agencies have highly developed and plentiful technical resources. Thus these agencies are able to develop adequate technical insights to allow the approval and rejection of proposed marine systems. In the U.S. the regulatory agencies generally do not have highly developed and plentiful technical resources, and thus, are much more reliant on industrial guidance and prescriptive codes and guidelines. In both cases, the regulatory agencies are very reliant on the engineering technology provided by industry. Thus, the regulatory codes and guidelines that are promulgated in one region are a reflection of the competency and capabilities of both the regulatory agencies and the industrial enterprises in a given region.

Engineering codes and guidelines for design, construction, maintenance, operation, and decommissioning of marine systems reflect the results of efforts to develop ‘consensus.’ Consensus development is essentially a leveling process that brings the backward up to an intermediate level of technology and brings the forward back to the same level. Thus, codes and guidelines represent a state-of-practice (SOP) for a given engineering community, at a given time, and for a given place. These codes and guidelines also attempt to embody proven technology. Rarely, is the state-of-art(SOA) included in these documents. There is an intentional time lag between the SOA and the SOP. This time lag is one that is intended to proof and validate the SOA for applications and required to develop consensus regarding how the SOA should be applied. However, the time lag between the SOA and its implementation into design codes and guidelines does not release the design engineer from responsibility to use appropriately the ‘best available and safest technology’ – the SOA.

In one way or another, all codes and guidelines for marine systems are based on RAM. RAM reflect the regional engineering, operating, regulatory, and societal interactions, values, and processes. In the most fundamental way, RAM is experience and time based. And, until the 1960’s this was the basic way in which engineering codes and guidelines for marine systems were developed. In the late 1960’s, explicit use was made of quantitative RAM processes; probability based RAM. In its most mature form, probability based RAM has been used as a compliment to experienced based RAM. The North Sea community has been very progressive in adopting and applying probability based RAM methods as an explicit part of development of engineering codes and guidelines. Probability based RAM were employed in the majority of Safety Cases that were required in the U. K. sector of the North Sea following the Piper Alpha catastrophe. The U. S. Gulf of Mexico has been less progressive in adopting probability based RAM methods. The U. S. Gulf of Mexico codes and guidelines have been based much more on experienced based RAM methods, and to a much lesser extent on probability based RAM methods. Most in the U. S. engineering community regard probability based RAM methods with great suspicion, relying to a much greater extent on qualitative and experienced based RAM methods. The records of failures and successes of marine systems in these two areas do not clearly speak in favor of one approach or the other. Perhaps, there are different ways to achieve desirable quality and reliability in marine systems, and these different ways must reflect the regional ‘environments’ (engineering, regulatory, social) in which they are applied. Perhaps, these different ways are required so that the local environments understand the background, applications, exceptions, and limitations of the codes and guidelines.

Presently, most engineering codes and guidelines address the hardware, equipment, and structure elements of marine systems. In only a few instances are there definitive and explicit provisions for the human elements that are a part of these systems. Construction of marine systems seems to be one of the most progressive in explicit recognition of quality assurance and quality control (QA/QC), personnel selection, training and qualification, worker safety and other definitive measures to assure that the human and organizational factors are addressed. Operations has recognized the importance of the human and organizational factors, and ‘first generation’ codes and guidelines are beginning to appear. Design and maintenance seem to be much farther behind in such recognition and provisions. There has been a proliferation of marine worker safety and operations safety guidelines; however, it is rare to see any direct connection between the hardware components of the guidelines and the human components. A few guidelines have begun to appear that address the competency of the organization and management system; but, their implementation in any really meaningful way has not been apparent.

Another present trend to be noted is the trend to develop international codes and guidelines for marine systems, e.g., by the International Standards Organization (ISO). On one hand, this development is commendable. It represents an attempt to standardize how marine systems are designed, constructed, maintained, operated, and decommissioned. The process of consensus development is far more difficult. ISO is essentially an industrial code and guideline development forum. And, the unique regional and regulatory aspects associated with different geographic areas must be subsumed in some way. Proposed ISO ‘regional annexes’ are intended allow the unique social, regulatory, and engineering to be recognized. However, for those regions that do not have the resources or backgrounds to develop such annexes, they will be impelled to either adopt the general ISO guidelines or to adopt some other appropriate guidelines. And again, at present, these codes and guidelines largely address the hardware, equipment, and structure aspects of marine systems. The human and organizational factors are much farther behind and generally attempts are made to recognize these factors in the forms of QA/QC measures and worker safety measures.

What about the future? One thing for sure, it will not be the same as the present. The author believes that the primary change in the future will be how RAM is integrated into engineering codes and guidelines for marine systems, and specifically how human and organizational factors are addressed in these codes and guidelines. This will be a unification of the concerns for hardware with the concerns for people and their organizations that design, construct, operate, maintain, and eventually decommission the hardware. There will be much greater attention paid to the organizational aspects that influence quality and reliability. Industry will be increasingly pressured to find more efficient and effective ways to conduct their business. Most societies that have significant investments in marine systems increasingly recognize the requirements for cost effectiveness, quality, and reliability of these systems. Environmental concerns are paramount, and people are certainly a part of the environment. Thus, there will be significant pressures on industry to become more efficient, yet at the same time, there will be pressures to achieve higher degrees of quality and reliability. Achieving balance among the competing constraints will not be easy.

First, it is clear the future developments of marine systems is happening at a far faster pace and on a much higher plane of technology. Experienced based trial-and-error based RAM will not suffice. The potentials for unexpected negative consequences associated with the higher plane of technology must also be recognized. Thus, more advanced RAM approaches will be needed. In addition, it is clear that if significant improvements in the quality and reliability of marine systems are to be efficiently achieved, then there must be an increase in the effectiveness of how the human and organizational factors are assessed and managed. Recent experience has more than adequately demonstrated that the primary challenge to quality and reliability of marine systems is not fundamentally associated with the structure, hardware, and equipment aspects of these systems. Efficient and effective improvements are fundamentally associated with the human and organizational factor aspects of these systems. The challenge is to develop and adopt RAM approaches that are primarily appropriate to address the human and organizational factor aspects.

RAM PIPE REQUAL

The fundamental steps of the RAM PIPE REQUAL approach are identified in Fig. 1. The steps may be summarized as follows:

Identification – this selection is based on an assessment of the likelihood of finding significant degradation in the quality (serviceability, safety, durability, compatibility) characteristics of a given pipeline system, and on an evaluation of the consequences that could be associated with the degradation in quality. The selection can be triggered by either a regulatory requirement or by an owner’s initiative, following an unusual event, an accident, proposed upgrading of the operations, or a desire to significantly extend the life of the pipeline system beyond that originally intended.

Condition survey – this survey includes the formation of or continuance **of** a databank that contains all pertinent information the design, construction, operation, and maintenance of a pipeline system. Of particular importance are identification and recording of exceptional events or developments during the pipeline system history. Causes of damage or defects can provide important clues in determining what, where, how ,and when to inspect and/or instrument the pipeline system. This step is of critical importance because the RAM PIPE process can only be as effective as the information that is provided for the subsequent evaluations (garbage in, garbage out).

Results assessment – this effort is one of assessing or screening the pipeline system based on the presence or absence of any significant signs of degradation its quality characteristics. The defects can be those of design, construction, operations, or maintenance. If there appear to be no potentially significant defects, the procedure becomes concerned with engineering the next IMR cycle. If there appear to be potentially significant defects, the next step is to determine if mitigation of these defects is warranted. Three levels of assessment of increasing detail and difficulty are proposed: Level 1 – Qualitative (Scoring, Muhlbauer 1992; Kirkwood, Karam 1994), Level 2 – Simplified Qualitative – Quantitative (Bea, et al 1998), and Level 3 – Quantitative (Quantitative Risk Assessment, QRA, Nessim, Stephens 1995; Bai, Song 1998; Collberg, et al 1996).

The basis for selection of one these levels is one that is intended to allow assessment of the pipeline with the simplest method. The level of assessment is intended to identify pipelines that are clearly fit for purpose as quickly and easily as is possible, and reserve more complex and intense analyses for those pipelines that warrant such evaluations. The engineer is able to choose the method that will facilitate and expedite the requalification process. There are more stringent Fitness for Purpose (FFP) criteria associated with the simpler methods because of the greater uncertainties associated with these methods, and because of the need to minimize the likelihood of ‘false positives’ (pipelines identified to FFP that are not FFP).

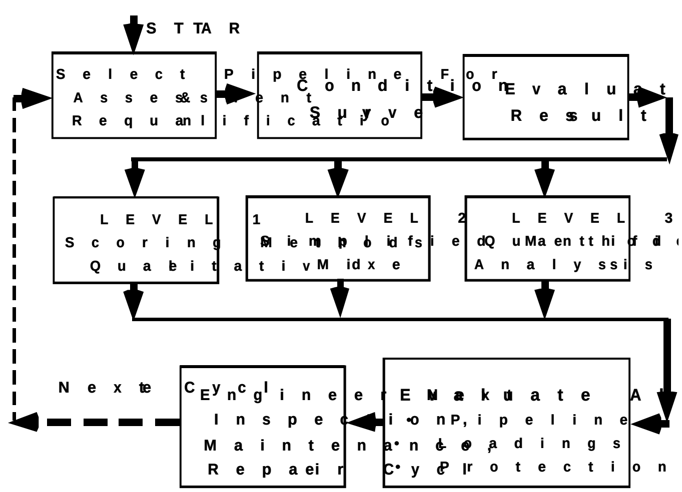

Fig. 1 – RAM PIPE Approach

Mitigation measures evaluation – mitigation of defects refers to prioritizing the defects to remedied (first things first), and identifying practical alternative remedial actions. The need for the remedial actions depends on the hazard potential of a given pipeline system, i.e., the likelihood that the pipeline system would not **perform** adequately during the next RAM PIPE cycle. If mitigation appears to be warranted, the next step is to evaluate the alternatives for mitigation.

Evaluating alternatives – mitigation alternatives include those concerning the pipeline itself (patches, replacement of sections), its loadings (cover protection, tie-downs), supports, its operations (pressure de-rating, pressure controls, dehydration) maintenance (cathodic protection, corrosion inhibitors), protective measures (structures, procedures, personnel), and its information (instrumentation, data gathering). Economics based methods (Kulkarni, Conroy 1994; Nessim, Stephens 1995), historic precedents (data on the rates of compromises in pipeline quality), and current standards of practice (pipeline design codes and guidelines, and reassessment outcomes that represent decisions on acceptable pipeline quality) should be used as complimentary methods to evaluate the alternatives and the pipeline FFP. An important alternative is that of improving information and data on the pipeline system (information on the internal characteristics of the pipeline with instrumentation – 'smart pigs' and with sampling, information on the external characteristics of the pipeline using remote sensing methods and on-site inspections).

Implementing Alternatives – once the desirable mitigation alternative has been defined, the next step is to engineer that alternative and implement it. The results of this implementation should be **incorporated** into the pipeline system condition survey – inspection databank. The experiences associated with implementation of a given IMR program provide important feed-back to the RAM PIPE process.

Engineering the next RAM PIPE cycle – the final step concluding a RAM PIPE cycle is that of engineering and implementing the next **IMR** cycle. The length of the cycle will depend on the anticipated performance of the pipeline system, and the need for and benefits of improving knowledge, information and data on the pipeline condition and performance characteristics.

EXAMPLE

To illustrate application of the foregoing developments, a Level 2 simplified qualitative – quantitative analysis approach will be utilized to evaluate in-place wall thickness requirements for pressure containment - burst capacity of a 508 mm (20-in) diameter, 12.7 mm (0.50 in) wall thickness gas pipeline operated by PEMEX in the Bay of Campeche. This pipeline was installed in 1980 and was constructed using X52 steel. The pipeline transports gas and oil. It is desired to requalify this pipeline for another 12 years of life (total life of 30 years). This example will be developed for both instrumented (smart piged) and un-instrumented conditions.

RELIABILITY FORMULATION

In this approach, pipeline strength was formulated in terms of the capacity of the pipeline to withstand the imposed pressures (internal, external) without loss of containment (rupture). The allowable burst pressure, Pb, was formulated as:

$$Pb = f\ 2\ Smts\ (t - d) / (D - t)$$

where f is the reassessment factor, d is the expected maximum depth of corrosion in the pipeline, t is the nominal thickness of the pipeline, D is the nominal diameter of the pipeline, and Smts is the specified minimum tensile strength of the pipeline steel.

A RAM based formulation of the foregoing developments can be developed as follows presuming that the demand (operating pressure) and capacity (pipeline burst pressure) are Lognormally distributed variables:

$$Pf = P\ (p_O \quad p_B)$$

where Pf is the probability of failure, p_O is the maximum net (internal – external) operating pressure, and P (X) is read as the probability of (X).

$$Pf = 1 - \Phi\{ [\ln (p_{B50} / p_{O50})] / [(\sigma^2_{pB} + \sigma^2_{pO})^{0.5}]\}$$

where Φ is the standard cumulative Normal distribution, p_{B50} is the 50th percentile (median) burst pressure, p_{O50} is the 50th percentile maximum operating pressure, σ_{pB} is the standard deviation of the logarithms of the burst pressure, and σ_{pO} is the standard deviation of the logarithms of the maximum operating pressures.

$$\beta = \ln (p_{B50} / p_{O50}) / \sigma = \ln FS_{pB/O\ 50} / \sigma$$

β is the Safety Index, $FS_{pB/O\ 50}$ is the central or median Factor of Safety between the pipeline burst pressure and the maximum operating pressure, and σ is the total uncertainty in the pipeline burst pressure and operating pressure.

$$p_B = p_O\ (B_{pO} / B_{pB}) \exp (\beta \sigma) = p_O\ B \exp (\beta \sigma)$$

p_B is the 'nominal' burst pressure, p_O is the 'nominal' maximum operating pressure, B_{pO} is the median 'Bias' in the nominal burst pressure, B_{pB} is the median Bias in the nominal maximum operating pressure, and B is the resultant median Bias in the nominal burst and operating pressures. Bias is defined as the ratio of the true value to the nominal (predicted, calculated) value.

It is to be noted that for the premises of this development (Lognormally distributed independent demands and capacities) that the forgoing formulations are 'exact' expressions. Generally, a Lognormal

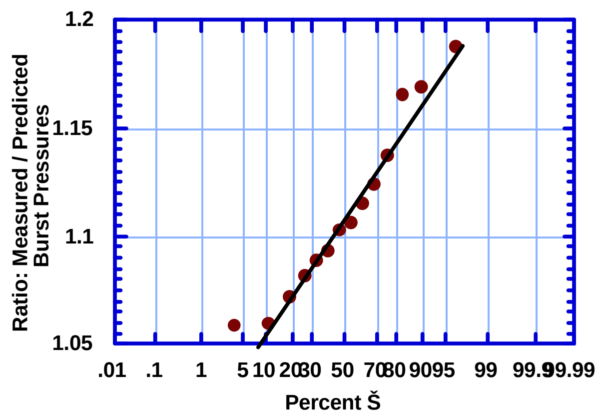

Fig. 2 - Ratio of measured to predicted burst pressures based on ultimate tensile strength

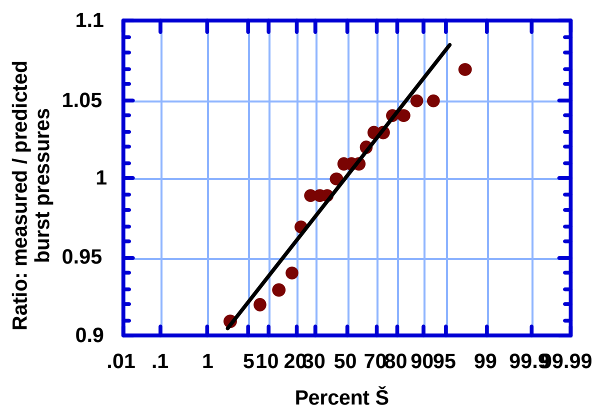

Fig. 3 - Ratio of measured and predicted burst pressures based on ultimate tensile strengths

distribution has been shown to provide good fits to both experimental and field data on pipeline capacities and demands (induced stresses). It is not necessary nor desirable in a Level 2 approach to utilize more complex formulations.

The reassessment factor can be expressed as:

$$f = [(B_{pC} / B_{pB}) \exp(\beta \sigma)]^{-1}$$

BURST CAPACITY WITH NO CORROSION

Fig. 2 shows the results from an analysis of 14 burst tests reported by Stewart and Klever (1998). The ordinate is the variable; in this case, the Bias. The abscissa is the cumulative probability (equal to or less than a given probability) of a given value of the variable.

These test data had diameter to thickness ratios in the range of 12 to 25. The predicted burst pressures were based on the analytical model cited above. The data indicate the median Bias (measured /.predicted burst pressures) is B = 1.11 and coefficient of variation of the Bias is V_B = 3.9 %. Given that the burst pressure formulation were based on the Von Mises ultimate tensile stress (Suts x 1.1), the bias is indicated to be close to unity and V_{BPb} = 2.7 % (Stewart, Kelver, 1998).

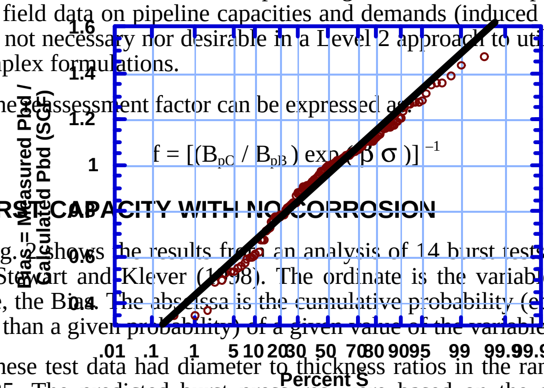

Fig. 4 – Bias in design formulation based on measured tensile strength

Fig. 3 shows results from analysis of 20 burst pressure tests on new pipe reported by Stewart, Klever, and Ritchie (1993). The test data were developed by 5 different groups. The test data indicate a median Bias of 1.0 and a coefficient of variation in the bias of V_{BPb} = 5.1 %. The variability developed by the various groups that performed the tests apparently is responsible for the larger coefficient of variation in the burst pressure bias.

BURST CAPACITY WITH CORROSION

Fig. 4 summarizes results from analysis of the database on the burst pressures associated with corroded pipelines assembled during the RAM PIPE REQUAL Phase 1 Project (Bea, et al, 1998). The database includes more than 150 physical tests on corroded and simulated corroded pipeline specimens.

The formulation used to assess the burst capacities was:

$$Pb = 2\ Sts\ (t - d) / (D - t)\ SCF$$

$$SCF = 1 + 2\ (d / R)^{0.5}$$

where Sts is the measured ultimate tensile strength, and SCF is the stress concentration factor due to the corrosion feature with maximum depth.

The corrosion induced SCF is a function of the depth of corrosion, d, and the pipeline radius, R. This is the SCF (maximum hoop stress / nominal hoop stress) that is due to a notch of depth d in the pipeline cross section that has a radius R. For this application, the radius of the notch was taken to be the radius of the pipeline. This formulation has a median bias of unity, B_{50} = 1.01, and a coefficient of variation of the bias of V_B = 24 %.

When the analysis of the test data was performed using the specified minimum tensile strengths, the median Bias was 1.16 and the Coefficient of Variation of the Bias was 23 %. The minimum tensile strengths were defined at minus 3 standard deviations from the mean tensile strength. The test data indicate that the burst pressure capacities are Lognormally distributed (Fig. 4).

This formulation does not explicitly account for the area dimensions of the corrosion (length, width). This formulation develops a Bias that is comparable with other formulations that do account for the corrosion plan dimensions (Bai, Xu, Bea, 1997). This formulation was developed because in a Level 2 assessment for un-instrumented pipelines it is difficult to accurately estimate the

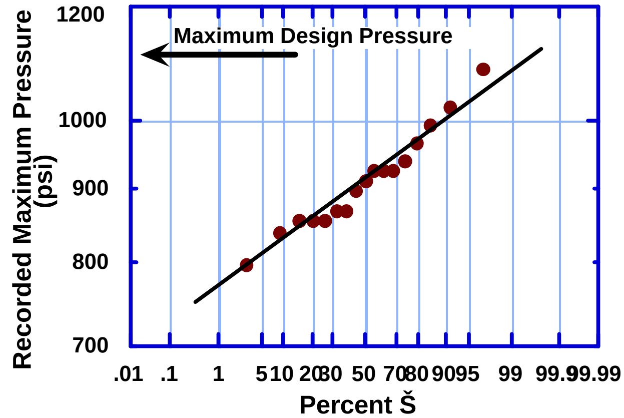

Fig. 5 – Recorded maximum operating pressures on a 20-inch diameter gas pipeline during a one month period

maximum corrosion depth; the area dimensions are even more difficult to estimate. The area dimensions are also difficult to obtain accurately for instrumented pipelines.

PIPELINE PRESSURE VARIABILITY

Fig. 5 summarizes the maximum operating net (minus external hydrostatic) pressures that were recorded on the 20-inch diameter gas pipeline that is to be requalified for service during a one month period. The field data indicate that the maximum pressures are Lognormally distributed (Fig. 5) The mean maximum operating pressure is 900 psi (pounds per square inch). The Coefficient of Variation of the maximum operating pressure is 8 %. The ratio of the mean maximum operating pressure to the maximum design pressure is 80 %.

Pipeline CORROSION – Not Instrumented

Based on data provided by PEMEX and IMP, Fig. 6 shows measured corrosion rates in Bay of Campeche gas pipelines as a function of the age of the pipelines. Zones A and B are located on the platform processing decks. Zones C and D are the vertical pipeline runs in the atmospheric and tidal range. Zones E and F are submerged (riser and on sea floor). There does not appear to be a systematic change in the corrosion rate ranges with the Zones.

There is a notable decrease in the corrosion rate with the age of the pipeline. To characterize the variabilities associated with the pipelines, the data for pipelines having ages in the range of 15 years to 18 years will be used.

Fig. 7 summarizes the probability distributions of the corrosion rates for gas pipelines for service periods in the range of 15 to 18 years. The mean rate for gas pipelines is 0.076 mm (0.003 inches) per year. The Coefficient of Variation of the corrosion rate is 50 % to 80 %.

Measured data on corrosion rates are not always available. In the Level 2 approach, a qualitative – quantitative approach was developed to estimate the loss in wall thickness of the pipeline due to corrosion. The loss of pipeline or riser wall thickness due to corrosion (d) was formulated as follows:

$$d = d_i + d_e$$

where d_i is the loss of wall thickness due to internal corrosion and d_e is the loss of wall thickness due to external corrosion.

The loss of wall thickness due to internal and/or external corrosion ($d_{i/e}$) was formulated as follows (Elsayed, Bea, 1997):

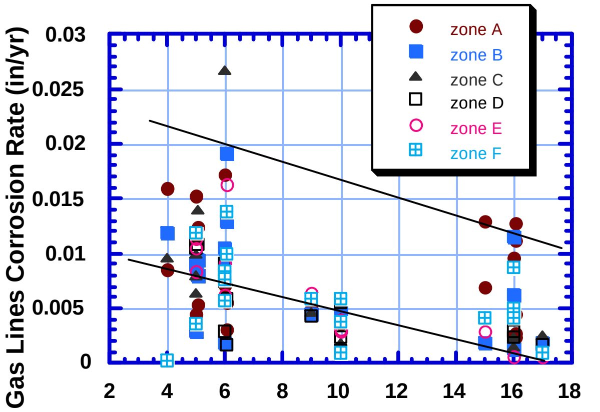

Fig. 6 – Measured corrosion rates in Bay of Campeche gas pipelines

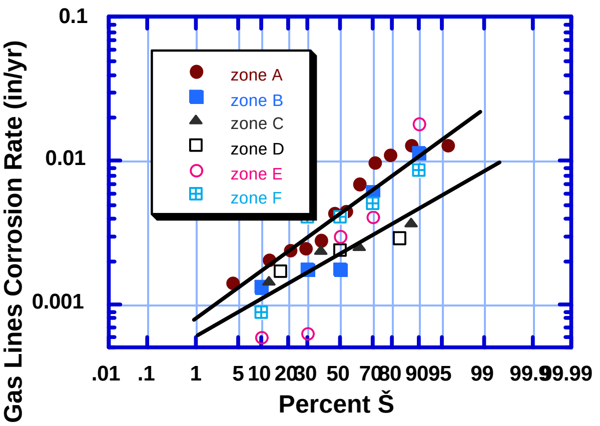

Fig. 7 – Probability distributions of corrosion rates of gas pipelines

$$d_{i/e} = \alpha_{i/e}\, \nu_{i/e}\, (Ls - Lp_{i/e})$$

where $\nu_{i/e}$ is the average (mean during service life) corrosion rate, $\alpha_{i/e}$ is the effectiveness of the inhibitor or protection (1.0 is perfect protection, and 10.0 is little effective protection), Ls is the service life of the pipeline or riser (in years), and $Lp_{i/e}$ is the 'life' of the initial protection provided to the pipeline.

This model assumes that there are no inspections and repairs performed during the service life of the pipeline or riser to maintain the strength integrity of the pipeline to carry pressure. Maintenance is required to preserve the protective management measures employed (e.g. renew coatings, cathodic protection, and inhibitors). The corrosion management is 'built-in' to the pipeline or riser at the start of the service period. Inspections and maintenance are performed to disclose unanticipated or unknowable defects and damage (due to accidents).

Stated another way, when an existing pipeline is requalified for service, inspections should be performed to disclose the condition of the pipeline and riser. Then an assessment should be performed to determined if it is fit for the proposed service. Alternative management of the pipeline could be to de-rate it (reduce allowable operating pressures), protect it (inhibitors, cathodic protection), repair it (doublers, wraps), or replace it.

For design and requalification , the corrosion rate is based on the owner/operators evaluation of the corrosivity of the fluids and/or gases transported inside the pipeline or riser, and of the corrosivity of the external environment conditional on the application of a certain protection or 'inhibition' program. Table 1 summarizes suggested median corrosion rates, their variabilities (standard deviations of the

Table 2 - Internal and External Inhibitor Efficiency

Descriptor	Inhibitor Efficiency	Inhibitor Efficiency Variability %
Very Low	10.0	30
Low	8.0	25
Moderate	5.0	20
High	1.0	15
Very High	1.0	10

Ta... Va...

Very Low	0.001	10
Low	0.01	20
Moderate	0.1	30
High	1.0	40
Very High	10.0	50

logarithms of the corrosion rates, approximately the coefficient of variation of the corrosion rates) and the linguistic variables used to describe these corrosion rates (Elsayed, Bea, 1997; NACE, 1992).

For example, a dehydrated sweet gas would generally have a low to very low corrosion rate (0.001 to 0.01 mm/year), particularly if inhibitors were used to protect the steel. A 'normally' dehydrated sweet oil without inhibitors could have a moderate corrosion rate (0.1 mm/year). A pipeline transporting high temperature salt water could have a corrosion rate that would be High to Very High (1.0 to 10.0 mm/year). Sour wet gas without any inhibitors could have similar corrosion rates (in addition to degrading the steel material properties).

A riser in the splash zone in the Gulf of Mexico without coating protection could have a corrosion rate that is High (1 mm/year). This zone would extend from mean low water to about 4 m above mean low water. Below this zone, the corrosion rate would be Moderate (0.1 mm/year), although local riser connections and other elements that could lead to local corrosion or pitting could have a corrosion rate that would be High (1.0 mm/year). An unprotected pipeline could be expected to have an external corrosion rate that would be Moderate (0.1 mm/year), unless there were other factors that could increase this rate (very high water velocities, severe erosion caused by sediment movements).

In this development, the effectiveness of corrosion management is expressed with two parameters, the inhibitor efficiency ($\alpha_{i/e}$) and the life of the protection ($Lp_{i/e}$). If the inhibitor (e.g. coating, dehydration, chemical inhibitor, cathodic protection) were 'perfect', then $Lp_{i/e}$ would equal 1.0. If experience had indicated otherwise, then the inhibitor efficiency and the associated variability / uncertainty could be introduced as summarized in Table 2.

The life of the protection reflects the operator's decision regarding how long the protection that will be provided will be effective at preventing steel corrosion. For example, the life of high quality external coatings in the absence of mechanical damage can be 10 years, where the life of low quality external coatings with mechanical damage can be 1 year or less. Another example would be cathodic protection that could be reasonably provided to protect the pipeline for a period of 10 years, but the expected life of the pipeline was 20 years. Thus, there would be 10 years of life in which the cathodic protection was not provided and the steel would be 'freely' corroding. Table 3 defines the general categories of the life of protective systems and their associated variabilities / uncertainties.

Given this information, pipeline owner / operators could define the expected life of the pipeline or riser (e.g. Very Long, Ls = 18 years), define the life of the protective management system that would be incorporated as a part of the pipeline or riser (e.g. Short, $Lp_{i/e}$ = 5 years), define the effectiveness of the protective management system (e.g. High, $\alpha_{i/e}$ = 1.0), and then based on the transported product and environment of the pipeline or riser, estimate the internal and external corrosion rates (e.g. νi = 0.1 mm/year, νe = 0.0 mm/year). The estimated loss in wall thickness due to corrosion would then be determined as:

Table 3 - Expected Life of the Protective System ($Lp_{i/e}$)

Descriptor	$Lp_{i/e}$ (years)	$Lp_{i/e}$ Variability (%)
Very Short	1	30
Short	5	25
Moderate	10	20
Long	15	15
Very Long	20	10

$$d_{i/e} = \alpha_{i/e}\, \nu_{i/e}\, (Ls - Lp_{i/e}) = 1.0 \cdot 0.1 \text{ mm/y } (18 \text{ y} - 5 \text{ y}) = 1.3 \text{ mm}$$

Based on the First Order – Second Moment method to evaluate the uncertainties associated with the products of random variables, the estimated variability / uncertainty associated with this loss in wall thickness could be estimated as :

$$Vd = (0.15^2 + 0.30^2 + 0.25^2)^{0.5} = 0.42$$

The measured corrosion indicated a median corrosion rate of 0.08 mm per year for pipelines having ages in the range of 15 to 18 years. The background provided by the measurements would indicate a current (1998) corrosion loss of d = 1.44 mm. This corrosion loss is very close the d = 1.6 mm (0.063 in) estimated using the qualitative – quantitative approach.

For a total life of 30 years, the estimated expected loss in wall thickness would be d = 2.4 mm (based on the measurement based mean rate of 0.08 mm/y) to d = 2.5 mm (0.1 in based on qualitative – quantitative method). This estimated expected median loss in wall thickness would have a variability in the range of 0.42 to 0.50. A uncertainty of 0.45 will be used in this example.

The uncertainty associated with the original wall thickness is 2% (Bea, et al, 1998; Jaio, et al, 1997). The uncertainty associated with the expected remaining wall thickness of 0.4 inches would be 12 %:

$$Vt = [(0.5 \text{ in x } 0.02)^2 + (0.1 \text{ in x } 0.45)^2\,]^{0.5} / 0.4 = 0.12$$

The pipeline burst pressure for the projected 30 year corrosion loss can be calculated to be:

$$Pb = 2 \bullet 66{,}000 \text{ psi } (0.40 \text{ in}) / (20 \text{ in} - 0.5 \text{ in})\ 1.20 = 2{,}260 \text{ psi}$$

PIPELINE CORROSION – INSTRUMENTED

Instrumentation or ‘smart pigs’ can be used to help develop evaluations of corrosion rates and remaining wall thicknesses. These measurements can be used to help make evaluations of corrosion in comparable pipelines that can not be instrumented. It is important recognize that making evaluations of corrosion rates and wall thicknesses from the recordings have significant uncertainties (Bal, Rosenmoeller, 1997). The measurements can give both ‘false positives’ and ‘false negatives.’ The pigs can miss significant defects and indicate the presence of defects that are not present.

Fig. 8 shows a comparison of the Probability of Detection (POD) of corrosion depths (in mils, 50 mils = 1.27 mm) developed by three different ‘smart pigs’ (Magnetic Flux Leakage based instrumentation). This information was based on comparing measured results from sections of the Trans Alaska pipeline that were pigged and then excavated and the true corrosion depths determined (Rust, et al 1996; Vieth, et al 1996).

There is a dramatic difference in the performance characteristics of these three smart pigs. If this type of variability is to be avoided or minimized, then specifications and test runs must be developed to verify the ability of the pigs to detect corrosion damage. Specifications for intelligent pig inspections of pipelines need to be developed if consistent and repeatable results are to be realized (Shell International, 1996).

There are significant uncertainties in the depths of corrosion indicated by the pigs due to such factors as variable temperatures and degrees of magnetism, and the speed of movements of the pig (Bal, Rosenmoeller, 1997). Corrosion rates are naturally very variable in both space and time. Thus, if instrumentation is used to determine the wall thicknesses and corrosion rates, the uncertainties in these characteristics needs to be determined and integrated into the evaluations of the fitness for purpose of the pipeline.

Fig. 9 summarizes data for two of the smart pigs noted in Fig. 8. Both pigs tend to underestimate the corrosion depth. The uncertainties associated with the measured depths ranged from 35 % (for 50 mils depths) to 25 % (for 200 mils depths) (1 mil = 1 E-3 inch).

Fig. 10 shows results from an instrumentation of the example gas line based on use of a smart pig designated as ‘Pig C.’ The measured and corrected corrosion expressed as a percentage of the wall thickness is shown. The corrections reflect an evaluation of the Bias in the ‘calls’ (measured corrosion depths) of the pig.

RELIABILITY – INSTRUMENTED PIPELINES

For the instrumented pipelines, the expression for the probability of failure can be expressed as:

$$Pf = Pf_D + Pf_{ND}$$

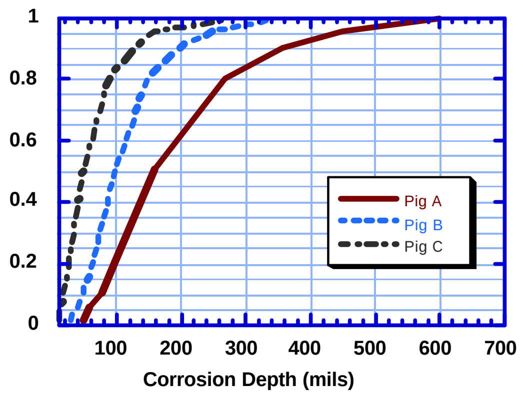

Fig. 8 – Probability of Detection Curves for Three Smart Pigs

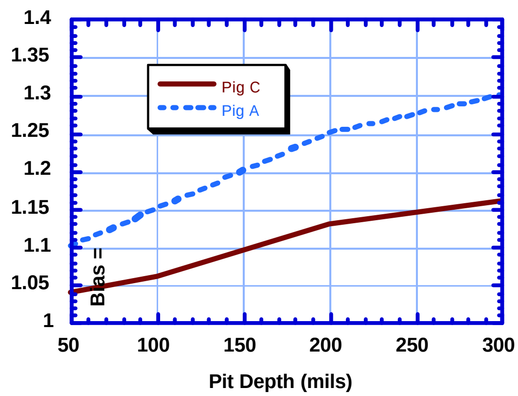

Fig. 9 – Bias in measured corrosion depths

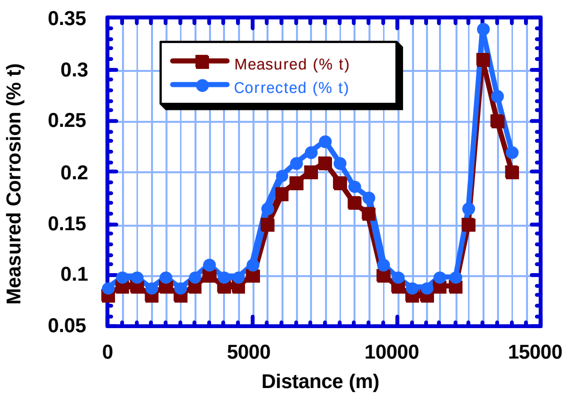

Fig. 10 – Pig C measured and corrected corrosion readings

where Pf_D is the probability of failure associated with the detected flaws and Pf_{ND} is the probability of failure associated with the non-detected flaws. The detected depth of corrosion must be corrected to the median depth of corrosion (Fig. 9). The detected depth of corrosion has a standard deviation of the Logarithms of the corrosion depths of σ_{lntc} = 0.25 to 0.35.

The probability of failure associated with the detected depth of corrosion is:

$$Pf_D = 1 - \Phi\{ [\ln (p_{B50} / p_{O50})] / [(\sigma^2_{pB} + \sigma^2_{pO})^{0.5}] \}$$

where Φ is the standard cumulative Normal distribution, p_{B50} is the 50th percentile (median) burst pressure, p_{O50} is the 50th percentile maximum operating pressure, σ_{pB} is the standard deviation of the logarithms of the burst pressure, and σ_{pO} is the standard deviation of the logarithms of the maximum operating pressures.

The pipeline burst pressure median value and uncertainty is determined as described earlier.

The probability of a corrosion depth, X, exceeding a lower limit of corrosion depth detectability, xo, is:

$$P[X \quad xo \mid ND] = P[X > xo] P[ND \mid X \quad xo] / P[ND]$$

P [X xo | ND] is the probability of no detection given X xo. P [X > xo] is the probability that the corrosion depth is greater than the lower limit of detectability. P [ND | X xo] is the probability of non detection given a flaw depth (Fig. 8). P [ND] is the probability of non detection across the range of flaw depths (Fig. 8) where:

$$P[ND] = 1 – P[D]$$

and:

$$P[ND] = \Sigma\, P[ND \mid X > xo]\, P[X > xo]$$

The probability of failure for non-detected flaws is the convolution of:

$$Pf_{ND} = \Sigma\, [Pf \mid X > xo]\, P[X \quad xo \mid ND]$$

Based these results and foregoing developments, Fig. 11 shows the annual probabilities of burst failure (detected and non-detected) of the pipeline. The operating pressure of 900 psi and a total uncertainty of 25 % was used to determine the probabilities of failure. This uncertainty reflects the uncertainties in the maximum operating pressures (8 %), the burst pressure calculations (23 %), and the pig called losses in wall thickness (30 %).

The annual probabilities of failure for the pipeline in its current condition range from Pf = 1 E-6 to Pf = 1 E-3. Two sections of the pipeline have experienced higher rates of corrosion than the other sections. These sections are associated with low elevations (sag) in the pipeline between 5,000 m and 10,000 m and at the pipeline riser – sea floor connection (13,000 m).

The measured corrosion losses were used to project the losses to a life of 30 years. The results are also summarized in Fig. 11. The increased corrosion has increased the probabilities of failure by factors of about 10 to 100. The annual probabilities of failure range from about 1 E-5 to 1 E-3 in the low sections of the pipeline to 1 E-1 at the pipeline riser – sea floor connection.

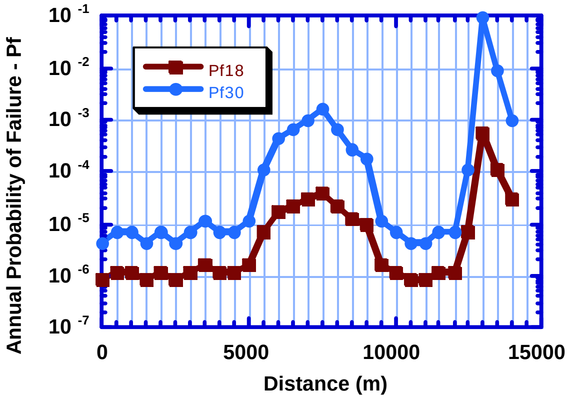

Fig. 11 – Probabilities of burst pressure failure

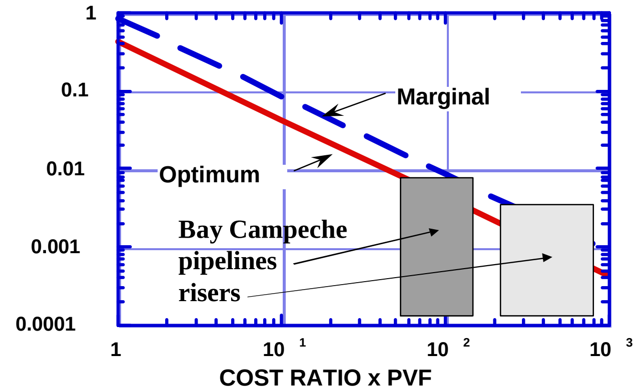

Fig. 13 – Economics based fitness for purpose guidelines

FITNESS FOR PURPOSE GUIDELINES

For the un-instrumented pipeline the evaluation of fitness for purpose will be based on determination of the reassessment factor, f:

$$f = [(B_{pO} / B_{pB}) \exp(\beta\, \sigma)]^{-1}$$

The reassessment factor is a function of the Biases in the operating pressures and the burst pressures (B_{pO}, B_{pB}), the total uncertainties in the operating pressures and burst pressures (σ), and the annual Safety Index (β). Fig. 12 shows the variation of the reassessment factor with the annual Safety Index for various total uncertainties. These results are based on median Biases in the operating pressures and burst pressures of unity.

The determination of the annual Safety Index for reassessment was based on three approaches: 1) Economics, 2) Historic Precedents, and 3) Standards of Practice.

Fig. 13 summarizes results from the Economics approach for the pipelines in the Bay of Campeche. The annual probability of insufficient quality (failure) is shown as a function of the Cost Ratio and present value function (PVF). the Cost Ratio is the ratio of the cost of failure associated with the pipeline (property, pollution, production) to the cost required to lower the probability of failure of the pipeline by a factor of 10. The present value function for short life pipelines is equal to the life in years. The PVF stipulated by PEMEX for these evaluations was PVF = 10.

The line labeled Optimum represents the sum of initial and future costs that is minimum. The line labeled Marginal represents the condition of a cost to reduce the probability of failure to benefit in reduction of the future cost ratio of unity. The Optimum line was used for defining the reliability associated with design of new pipelines. The Marginal line was used for defining the reliability associated with reassessment of existing pipelines.

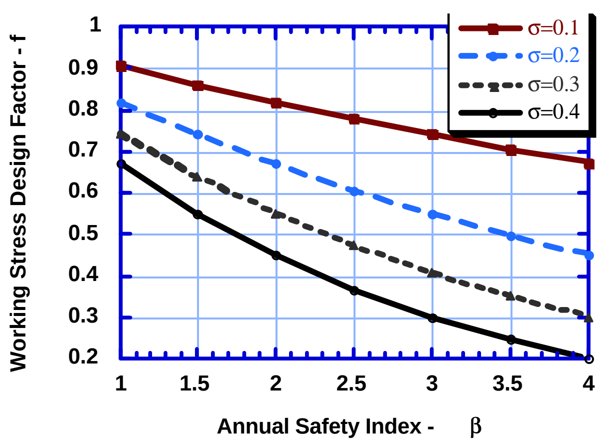

Fig. 12 – Reassessment factors

Annual Safety Indices for pipelines and risers of β = 3.4 and β = 3.8, respectively, were identified by PEMEX for development of the reassessment guidelines. These annual Safety Indices equate to annual probabilities of failure of Pf = 3.3 E-4 and Pf = 0.72 E-4, respectively.

These results can be compared with the basis for the DNV guidelines for design of pipelines (DNV, 1996). This basis indicates β = 3.8 to 4.4 for High Safety Class to β = 3.1 to 3.8 for Normal Safety Class. The values identified for the Bay of Campeche fall within these ranges.

Historic rates of failure of northern Gulf of Mexico oil and gas pipelines have ranged from about Pf = 0.5 E-3 to as high as Pf = 1.0 E-2 per year. Approximately half of these rates are due to corrosion related failures. Thus, the historic rates of failure that can be attributed to corrosion failures is about Pf = 2.5 E-4 to Pf= 5.0 E-3 per year. The values identified for the Bay of Campeche are somewhat more conservative that these historic rates of failure.

ASSESSMENT OF FITNESS FOR PURPOSE

Using a β = 3.4 for the example un-instrumented pipeline, the reassessment factor for a total uncertainty of 27 % and Bias of 0.86 would be f = 0.46 For β = 3.8 for pipeline risers, the reassessment factor would be f = 0.42. The uncertainty reflects the uncertainties in the maximum operating pressures (8 %), the burst pressure calculations (23 %), and the estimated loss in wall thickness (12 %). The total Bias reflects the median Bias in the calculation of the burst pressures (1 / 1.2) and a median Bias of 1.0 based on the maximum median operating pressure of 900 psi.

The allowable maximum operating pressure for the 30 year life pipeline would be:

$$P_{ba} = 2{,}260 \text{ psi } (0.46) = 1{,}040 \text{ psi}$$

The present median maximum operating pressure is 900 psi. Given this maximum operating pressure, the pipeline would be requalified for the proposed 30-years of service.

The allowable maximum operating pressure for the 30 year life riser section would be:

$$P_{ba} = 2{,}260 \text{ psi } (0.42) = 950 \text{ psi}$$

The present median maximum operating pressure of 900 psi would be acceptable for the riser.

The instrumented pipeline example for the projected 30-year corrosion conditions has annual probabilities of failure that range from Pf = 1 E-5 to Pf = 1 E-3 in the low section to 1 E-1 at the riser sea floor connection. The pipeline in the low section at the riser sea floor connection would need to be replaced or the operating pressures lowered.

CONCLUSIONS

A three pronged approach to RAM has been proposed that involves proactive, reactive, and interactive strategies and methods. The approach addresses the primary hazards to the quality and reliability of engineered systems: people and their organizations.

A general approach for design and requalification of pipeline systems has been proposed that utilizes qualitative, quantitative, and mixed qualitative – quantitative approaches. These approaches are complimentary. Each has its advantages and limitations. The simpler approaches are used to design and requalify the vast majority of pipelines. The more complex approach is reserved for the more complex problems and situations.

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